

Baryonic resonances close to the $\bar{K}N$ threshold: the case of $\Lambda(1405)$ in pp collisions

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We present an analysis of the $\Lambda(1405)$ resonance produced in the reaction $p + p \rightarrow \Sigma^\pm + \pi^\mp + K^+ + p$ at 3.5 GeV kinetic beam energy measured with HADES at GSI. The two charged decay channels $\Lambda(1405) \rightarrow \Sigma^\pm \pi^\mp$ have been reconstructed for the first time in p+p collisions. The efficiency and acceptance-corrected spectral shapes show a peak position clearly below 1400 MeV/c². We find a total production cross section of $\sigma_{\Lambda(1405)} = 9.2 \pm 0.9 \pm 0.7^{+3.3}_{-1.0} \mu\text{b}$. The analysis of its polar angle distribution suggests that the $\Lambda(1405)$ is produced isotropically in the p-p center of mass system.

Lying slightly below the $\bar{K} - N$ threshold ($\approx 30 \text{ MeV}/c^2$), the broad $\Lambda(1405)$ resonance is considered to be strongly linked to the antikaon-nucleon interaction. Hence the understanding of this resonance is mandatory to address this issue in hadron physics. It was first observed experimentally by studying its presence in the $\Sigma\pi$ exit channel in K^- -induced reactions [1]. From a theoretical point of view the $\Lambda(1405)$ is treated within a coupled channel approach, based on chiral dynamics, in which the low-energy $\bar{K} - N$ interactions can be handled [2]. In this Ansatz the $\Lambda(1405)$ appears naturally as

a dynamically generated resonance, resulting from the superposition of two components: a quasi-bound $\bar{K} - N$ state and a $\Sigma\pi$ resonance.

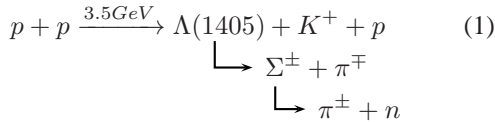
At present, the molecule-like character of the $\Lambda(1405)$ is commonly accepted. However, the contribution of the $\Sigma\pi$ channel to the formation process is still discussed controversially. Indeed phenomenological approaches differently from chiral-SU(3) predictions [3] support the hypothesis that the $\Lambda(1405)$ can be considered as purely a K^-p quasi-bound state and suggest experimental methods to test this Ansatz. In gen-

eral, models can be constrained above the $\bar{K} - N$ threshold by K^-p scattering data and by the measurements of the Kp , Kn scattering lengths extracted from kaonic atoms as shown in [4, 5]. Below threshold, the only experimental observable related to the $\bar{K} - N$ interaction is the $\Lambda(1405)$ spectral shape extracted from the decays $\Lambda(1405) \xrightarrow{\approx 100\%} (\pi\Sigma)^0$. The authors of reference [6] predict for the $\Lambda(1405)$ in the reaction $\gamma + p \rightarrow \Lambda(1405) + K^0$ that the spectral function of the three final states $\Sigma^-\pi^+/\Sigma^0\pi^0/\Sigma^+\pi^-$ should differ because of the interference of the isospin 0 and 1 channels. In fact, the measured invariant mass distributions of the $\Sigma\pi$ states have different shapes [7], which also vary as a function of the photon energy, but the observed shifts of the distributions are not described by the models.

Furthermore, the approach [8] predicts that the coupling of the resonance to the quasi-bound $\bar{K} - N$ state and the $\Sigma\pi$ pole depends on the initial state configuration. The observed line shape and pole position of the $\Lambda(1405)$ is expected to vary for different reactions. Data exploiting pion [9] and kaon [10] beams are scarce, and the reaction $p + p \rightarrow p + \Lambda(1405)(\rightarrow \Sigma^0 + \pi^0) + K^+$ has been studied hitherto only by the ANKE experiment [11] at a beam momentum of 3.65 GeV/c.

Based on the analysis of the reaction $p + p \rightarrow p + K^+ + (\Sigma + \pi)^0$ at 3.5 GeV kinetic beam energy, measured by HADES [12], we present the first data on the decay of the $\Lambda(1405)$ resonance into the $\Sigma^\pm\pi^\mp$ final states. The spectral shapes, the polar production angle, and the production cross-section of the $\Lambda(1405)$ are discussed.

The properties of the $\Lambda(1405)$ resonance have been studied in the associated production together with a proton and a K^+ followed by the decay into $\Sigma^\pm + \pi^\mp$ pairs where a branching ratio of 33.3 % for each decay channel is assumed:



The assumption about the branching ratios of the $\Lambda(1405)$ decays is motivated by the consideration of the isospin symmetries [13] and does not take into account the interference between the two isospins states 1 and 0. For an exclusive analysis, all charged particles (p , K^+ , π^+ , π^-) in the final state have been identified employing the momentum dependent dE/dx and velocity information [14]. The neutron appearing in the reaction (1) has been reconstructed via the missing mass to the four charged particles p , π^\pm , π^\mp , K^+ and has been selected via a 2.4σ cut around the nominal neutron mass (see Fig. 1 in [15]). The intermediate Σ^+ and Σ^- hyperons have been reconstructed via the missing mass to the proton, the K^+ and either the π^- or the π^+ (see Fig. 4 in [15]). 3σ mass cuts around the nominal masses of the Σ^+ and Σ^- hyperons allow to extract the $\Lambda(1405)$ signal corresponding to the two decay modes into $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$. After the subtraction of the misidentification background due to the limited kaon identification [14], the $\Lambda(1405)$ spectral shape for both decay channels can be analyzed in the missing mass spectra to the proton and the K^+ ,

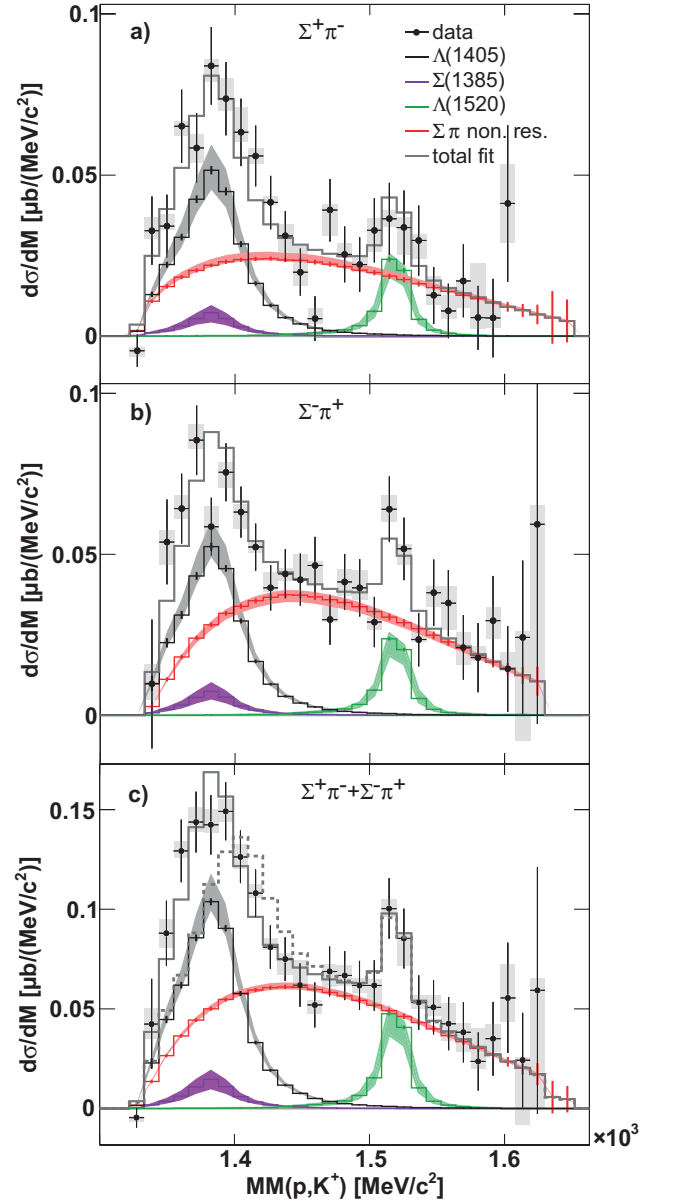
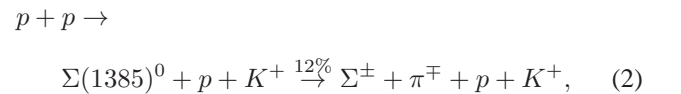


FIG. 1. (Color online) Missing mass $MM(p, K^+)$ distributions for events attributed to the $\Sigma^+\pi^-$ decay channel a) and to the $\Sigma^-\pi^+$ decay channel b). Panel c): sum of both spectra from panels a) and b). The gray dashed histogram shows the sum of all simulated channels if the $\Lambda(1405)$ is simulated with its nominal mass of 1405 MeV/c². Colored histograms in the three panels indicate the contributions of the channels (1-5) obtained from simulations. Data and simulations are acceptance and efficiency corrected. The gray boxes indicate systematic errors.

$MM(p, K^+)$. Figure 1 shows the $MM(p, K^+)$ distributions for the $\Sigma^+\pi^-$ a) and $\Sigma^-\pi^+$ b) decay channels. The black dots correspond to the experimental data. Together with the reaction (1) the following contributions have been considered:



$$\Lambda(1520) + p + K^+ \xrightarrow{28\%} \Sigma^\pm + \pi^\mp + p + K^+, \quad (3)$$

$$\Sigma^+ + \pi^- + p + K^+, \quad (4)$$

$$\Delta^{++}(1232) + \Sigma^- + K^+ \xrightarrow{100\%} p + \pi^+ + \Sigma^- + K^+. \quad (5)$$

Full scale simulations of these channels have been carried out and the relative contribution of each of them has been evaluated from a simultaneous fit to the two missing mass distributions $MM(p, K^\pm)$ together with the two $MM(p, K^+)$ distributions [15]. The area around $1400 \text{ MeV}/c^2$ for $MM(p, K^+)$ has been excluded from the fit in order to not bias the finally extracted shape of the $\Lambda(1405)$ resonance by the simulated $\Lambda(1405)$ shape. In total, a normalized χ^2 value of $\chi^2/\text{ndf} \approx 1.3$ has been obtained. Figure 1 shows the contributions of the different channels together with their incoherent sum (gray histogram, solid line).

The data and the full-scale simulations shown in Fig. 1 a)-c) are corrected for acceptance and efficiency and the statistical and systematic errors for both, experimental data and simulations are displayed. The finite geometrical acceptance of HADES and the total reconstruction efficiency have been calculated using full-scale simulations of the channels (1-5), including the correct angular distribution for these channels as described below. The systematic errors shown in Fig. 1 have been obtained by varying the selection cuts by $\pm 20\%$ and the angular distribution of the simulated reactions (4) and (5) by $\pm 30\%$.

The experimental data (black dots) in Fig. 1 a) and b) show two distinct peak structures. The one slightly below $1400 \text{ MeV}/c^2$ is mainly due to the $\Lambda(1405)$ resonance, whereas the second peak around $1500 \text{ MeV}/c^2$ is attributed to the $\Lambda(1520)$ resonance. The relative contribution of $\Lambda(1405)$ and $\Sigma(1385)^0$ can not be determined by fitting the simulations to the experimental data since their mass spectra overlap completely. However, in the analysis of the neutral decay channels the two particles can be separated to some extent. The $\Lambda(1405)$ has a 33.3 % branching ratio into the $\Sigma^0\pi^0$ channel whereas this decay is forbidden for the $\Sigma(1385)^0$ due to isospin conservation. By analyzing the decays $\Lambda(1405) \rightarrow \Sigma^0 + \pi^0$ and $\Sigma(1385)^0 \rightarrow \Lambda + \pi^0$ [16] the cross-section for the $\Sigma(1385)^0$ was estimated to be $\sigma_{\Sigma(1385)^0} = 5.56 \pm 0.48_{-1.06}^{+1.94} \mu\text{b}$. The uncertainty of the angular distribution of $\Sigma(1385)^0$ has been included in the systematic error of the production cross-section by considering the two extreme cases of an isotropic distribution for the $\Sigma(1385)^0$ and of the same angular distribution as measured for the $\Sigma(1385)^+$ [14]. The obtained cross-section for the $\Sigma(1385)^0$ has been utilized to calculate the relative contribution to the $MM(p, K^+)$ spectrum shown in Fig. 1 by the magenta histogram. The systematic uncertainties have been propagated accordingly. Figure 1 c) shows the sum of the distributions from the two final states $\Lambda(1405) \rightarrow \Sigma^\pm\pi^\mp$ for experimental data and simulations. The good agreement between the corrected experimental data and the simulation (gray histogram, solid line) is obtained by simulating the $\Lambda(1405)$ as a relativistic s-wave Breit-Wigner distribution with a width of $50 \text{ MeV}/c^2$ and a pole mass of $1385 \text{ MeV}/c^2$. Using instead the nominal mass of $1405 \text{ MeV}/c^2$ results in the gray dashed histogram in Fig. 1

c) which fails to describe the experimental $\Lambda(1405)$ peak structure. The difference is expressed by the two χ^2 values of 0.6 and 2.1 respectively.

A good fit is also obtained, if the cross-section of the $\Sigma(1385)^0$ is not fixed and the $\Lambda(1405)$ is generated with its PDG values for mass and width. In this scenario the production cross-sections obtained for the $\Lambda(1405)$ and $\Sigma(1385)^0$ are approximately 3 and $50 \mu\text{b}$ respectively. The cross-section of the $\Sigma(1305)^0$ would then largely exceed the value reported in [16] and also the measured cross-section for the $\Sigma(1385)^+$ ($22 \mu\text{b}$) in the same data sample. This contradicts the findings at higher energies reported in [18], where cross-sections of $7 \mu\text{b}$ and $15 \mu\text{b}$ are measured for the $\Sigma(1385)^0$ and $\Sigma(1385)^+$ hyperons, respectively, produced in p+p collisions at 6 GeV. These arguments strongly disfavor this second scenario. On the other hand, one should mention that, analog to the Söding mechanism [19], interferences of resonant and non-resonant amplitudes with the same exit channel can cause an apparent shift of the peak of the spectral distribution without a change of the $\Lambda(1405)$ pole mass. Our efficiency and acceptance-corrected experimental data are hence a perfect tool to test different theoretical models.

The different sources contributing to the missing mass spectra shown in Fig. 1 have been studied in terms of their polar angle (θ) in the p-p center of mass system. The results provide on the one hand constraints on possible production mechanisms of the $\Lambda(1405)$ and allow on the other hand to compute the acceptance corrections. The polar angle of the missing momentum vector to the $(p - K^+)$ system, $MV(p, K)$, has been investigated. The resulting angular distribution of $\cos(\theta_{\text{CMS}}^{\text{MV}(p, K)})$ has been divided into three intervals. Each of the three resulting subsamples is treated in the same way as described for the angle integrated event sample, meaning that the simulated distributions of $MM(K, p)$ have been fitted to the experimental ones. In the fits the polar angle distribution of the $\Sigma(1385)^0$ was assumed to be the same as reported in [14], for the $\Sigma(1385)^+$. Corrected experimental $MM(p, K^+)$ distributions like those in Fig. 1 have been obtained in each bin of $\cos(\theta_{\text{CMS}}^{\text{MV}(p, K)})$. The cross-sections of the reactions 1-5 are the integrals of the simulated distributions. The results are plotted as a function of $\cos(\theta_{\text{CMS}}^{\text{MV}(p, K)})$ in Fig. 2. The shown systematic errors are obtained by varying the different selection cuts as described above by $\pm 20\%$. The results suggest that the $\Lambda(1405)$ as well as the $\Lambda(1520)$ are produced rather isotropically, whereas the production in the channels (4) and (5) is obviously anisotropic. The observed angular distributions have been included by folding the simulations of the reactions (4) and (5) with the red curves shown in panel a) and b) of Fig. 2, respectively, whereas the $\Lambda(1405)$ and $\Lambda(1520)$ production has been simulated isotropically. These simulations have been used to produce the acceptance and efficiency corrections applied to the data shown in Figs. 1 and 2. The curvatures of the functions shown in panels a) and b) in Fig. 2 have been varied within 30 % and the simulations have been folded with the obtained angular distributions. The resulting uncertainty has been included in

the systematic errors shown by the gray shaded boxes in Figs. 1 and 2.

The simulation model obtained from this analysis has been tested for several other observables and overall a good agreement with the experimental data is obtained [17].

Finally our corrected spectra allow to extract cross-sections for the channels (1-5). This is again done by integrating the simulated spectra and using the statistical errors from the experimental data. We get the following values:

$$\sigma_{pp \rightarrow \Lambda(1405)pK^+} = 9.2 \pm 0.9 \pm 0.7^{+3.3}_{-1.0} \mu\text{b}, \quad (6)$$

$$\sigma_{pp \rightarrow \Lambda(1520)pK^+} = 5.6 \pm 1.1 \pm 0.4^{+1.1}_{-1.6} \mu\text{b}, \quad (7)$$

$$\sigma_{pp \rightarrow \Sigma^+ \pi^- pK^+} = 5.4 \pm 0.5 \pm 0.4^{+1.0}_{-2.1} \mu\text{b}, \quad (8)$$

$$\sigma_{pp \rightarrow \Delta^{++} \Sigma^- K^+} = 7.7 \pm 0.9 \pm 0.5^{+0.3}_{-0.9} \mu\text{b}. \quad (9)$$

The first error gives the statistical error, the second one gives the systematic error from the normalization to the p+p elastic cross-section and the last error is the error obtained from the systematic variations mentioned above. Figure 3 shows a compilation of the production cross-section as a function of the excess energy ϵ for the channels $p + p \rightarrow \Lambda + K^+ + p$

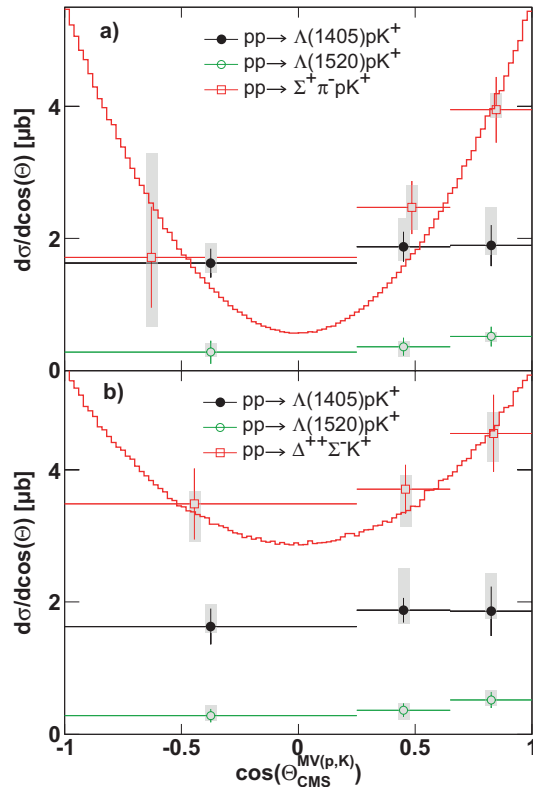


FIG. 2. (Color online) Differential cross-section for the different simulated reaction channels as a function of $\cos(\theta_{\text{CMS}}^{\text{MV}(p,K)})$ for the $\Sigma^+\pi^-$ decay channel a) and the $\Sigma^-\pi^+$ decay channel b). The cross-sections are obtained by integrating the simulations, which have been fitted to the experimental data. The gray boxes indicate the systematic errors. The full line shows the angular distribution used to fold the simulation of the reactions $p + p \rightarrow \Sigma^+ + \pi^- + p + K^+$ and $p + p \rightarrow \Delta^{++} + \Sigma^- + K^+$ respectively.

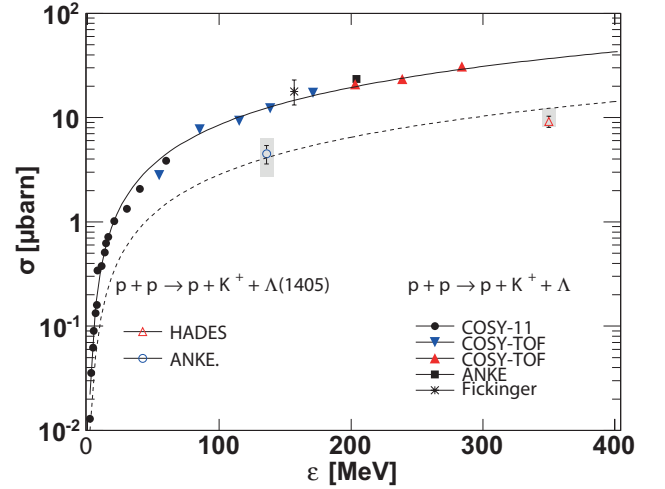


FIG. 3. Compilation of production cross-sections as a function of the excess energy ϵ for the reactions $p + p \rightarrow \Lambda + K^+ + p$ from [20], $p + p \rightarrow \Lambda(1405) + K^+ + p$ from [11] and this work. See text for details.

[20] and $p + p \rightarrow \Lambda(1405) + K^+ + p$ [11]. The solid curve shown in Fig. 3 corresponds to the parametrization of the Λ production discussed in [20]. The dashed curve has been obtained by scaling the parametrization of the Λ by a factor 1/3. One can see that the dependence of the $\Lambda(1405)$ production cross-section upon the energy seems to follow the same behaviour as exhibited by Λ production in p+p collisions.

The $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$ decay channels of the $\Lambda(1405)$ have been studied for the first time in p+p collisions at 3.5 GeV. These results can substantially contribute understanding the nature of $\Lambda(1405)$ which is considered as the key stone for the study of the $\bar{K} - N$ interaction. The obtained results indicate a shift of the $\Lambda(1405)$ resonance in p+p reactions to values clearly below 1400 MeV/ c^2 with a maximum of the mass distribution around 1385 MeV/ c^2 for both decay channels. If one considers the values of the masses of the two $\bar{K} - p$ and $\Sigma\pi$ poles recently constrained more precisely by new data on kaonic-hydrogen [21], our result suggests that in p+p collisions the contribution by the $\Sigma\pi$ pole to the formation of the $\Lambda(1405)$ might be dominant.

The here presented mass distributions differ from the one measured in γ - and K-induced reactions [7, 10] and also from the measurement of the $\Lambda(1405) \rightarrow \Sigma^0\pi^0$ in p+p at 2.85 GeV collisions [11] and the corresponding theoretical study [22]. The fact that the $\Sigma\pi$ spectra connected to the $\Lambda(1405)$ resonance strongly differ among different reactions indicates that the production mechanism depends upon the entrance channel and that precise measurements exploiting different beams are necessary together with a theory able to describe at the same time all the experimental results. However, by interpreting this result one should take into account that the interference effects between the different channels might play an important role.

The angular distributions of the $\Lambda(1405)$ and $\Lambda(1520)$ in the CMS are rather isotropic, suggesting a large momentum

transfer in the production mechanism. A total cross-section of $\sigma_{\Lambda(1405)} = 9.2 \pm 0.9 \pm 0.7^{+3.3}_{-1.0} \mu\text{b}$ was reconstructed, which is about a factor of two smaller than the cross-section extracted for the $\Sigma(1385)^+$ [14]. The comparison of the $\Lambda(1405)$ production cross-section with the systematics measured as a function of the excess energy for the $\Lambda p K^+$ final state shows that the two available data points are in agreement with the phase-space trend measured for the Λ production. A comparable production cross-section has been extracted for the reaction $pp \rightarrow \Delta^{++} \Sigma^- K^+$ underlining the role played by Δ resonances in the production mechanisms discussed here. Considering the hypothesis that the $\Lambda(1405)$ might be a doorway for the formation of kaonic bound states, the numbers presented here are a necessary bench mark for theory to correctly address the formation of states like ppK^-

produced in p+p collisions further decaying into $p + \Lambda$.

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